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Multiplicity-dependent enhancement of strange and multi-strange hadron production in proton-proton collisions at $\sqrt{s}$ = 7 TeV

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Abstract

The yields of strange (K^0_S, Λ, $\overline{\Lambda}$) and multi-strange (Ξ^-, $\overline{\Xi}^+$, Ω^-, $\overline{\Omega}^+$) hadrons are measured at midrapidity in proton-proton (pp) collisions at $\sqrt{s}$ = 7 TeV as a function of the charged-particle multiplicity density ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$). The production rate of strange particles increases faster than that of non-strange hadrons, leading to an enhancement of strange particles relative to pions, similar to that found in nucleus-nucleus collisions as well as in proton-nucleus collisions at the LHC. This is the first observation of an enhanced production of strange particles in high-multiplicity pp collisions. The magnitude of this strangeness enhancement increases with the event activity, quantified by $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$, and with hadron strangeness. It reaches almost a factor of two for the Ω at the highest multiplicity presented. No enhancement is observed for particles with no strange quark content, demonstrating that the observed effect is strangeness rather than mass related. The results are not reproduced by any of the Monte Carlo models commonly used at the LHC, suggesting that further developments are needed for a complete microscopic understanding of strangeness production and indicating the presence of a phenomenon novel in high-multiplicity pp collisions.

The production of strange hadrons in high-energy hadronic interactions provides a key tool to investigate the properties of Quantum Chromo-Dynamics (QCD), the theory of strongly-interacting matter. Unlike up (u) and down (d) quarks, which form ordinary matter, strange (s) quarks are not present as valence quarks in the initial state, yet they are sufficiently light to be abundantly created in the course of the collisions. During the early stages of high energy collisions, strangeness is produced in hard (perturbative) $2 \rightarrow 2$ partonic scattering processes by flavor creation ($gg \rightarrow s\bar{s}$, $q\bar{q} \rightarrow s\bar{s}$) and flavor excitation ($gs \rightarrow gs$, $qs \rightarrow qs$). Strangeness is also created during the subsequent partonic evolution via gluon splittings ($g \rightarrow s\bar{s}$). These processes tend to dominate the production of high transverse momentum (p_{T}) strange hadrons. At low p_{T} non perturbative processes like string fragmentation dominate the production of strange hadrons. As the strange quark is heavier than the up and down quarks, production of strange hadrons in fragmentation is generally suppressed relative to hadrons containing only light quarks. The amount of strangeness suppression in elementary (e^+e^- and pp) collisions is an important factor in Monte Carlo (MC) models. For these reasons, measurements of strange hadron production provide valuable input for their developments.

An enhanced production of strange hadrons was one of the earliest proposed indicators for the formation of a Quark-Gluon Plasma (QGP) state [1–3], as higher rates for strange quark production are expected in a highly-excited state of QCD matter. This strangeness enhancement is expected to be more pronounced for multi-strange baryons, and was indeed observed in collisions of heavy nuclei at the Super Proton Synchrotron (SPS), Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) [4–13]. The abundances of strange particles in heavy-ion (HI) collisions are compatible with those of a hadron gas in thermal and chemical equilibrium and can be described using a grand canonical statistical model [14, 15]. Extensions of the statistical description, like the strangeness canonical suppression [16] and the core-corona superposition [17, 18] models, can effectively produce a suppression of strangeness production in small systems. However, the fundamental origin of enhanced strangeness production is not known, and the measurements presented in this Letter may contribute to the microscopic understanding of it. Several effects, like near-side long-range correlations and mass-dependent hardening of p_{T} distributions, which in nuclear collisions are typically attributed to the formation of a strongly-interacting quark-gluon medium, have been observed in high-multiplicity pp and proton-nucleus collisions at the LHC [19–29]. Yet, enhanced production of strange particles as a function of the charged-particle multiplicity density ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$), originally considered to be another signature of QGP formation in nuclear collisions [1–3], has so far not been observed in pp collisions. The study of pp collisions at high multiplicity is thus of considerable interest as it opens the fascinating possibility of understanding phenomena known from nuclear reactions microscopically.

In this Letter, we present the multiplicity dependence of the production of primary strange (K^0_S, Λ, $\overline{\Lambda}$) and multi-strange (Ξ^-, $\overline{\Xi}^+$, Ω^-, $\overline{\Omega}^+$) hadrons in pp collisions at $\sqrt{s}$ = 7 TeV. The measurements have been performed at midrapidity, $|y| < 0.5$, with the ALICE detector [30] at the LHC. Primary particles are defined as prompt particles produced in the collisions, including all decay products, except products from weak decays of light-flavor hadrons and of muons. Similar measurements on the multiplicity and centrality dependence of strange and multi-strange hadron production have been performed by ALICE in proton-lead (p–Pb) collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV [25, 27] and in lead-lead (Pb–Pb) collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV [13, 31].

A detailed description of the ALICE detector and of its performance can be found in [30, 32]. We briefly outline the main detectors utilized for this analysis. The V0 detectors are two scintillator hodoscopes employed for triggering, background suppression and event-class determination. They are placed on either side of the interaction region at $z = 3.3$ m and $z = -0.9$ m, covering the pseudorapidity regions $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. Vertex reconstruction, central-barrel tracking and charged-hadron identification are performed with the Inner Tracking System (ITS) and the Time-Projection Chamber (TPC), which are located inside a solenoidal magnet providing a 0.5 T magnetic field. The ITS is composed of six cylindrical layers of high-resolution silicon tracking detectors. The innermost layers consist of two arrays of hybrid Silicon Pixel Detectors (SPD) located at average radii 3.9 and 7.6 cm from the beam axis and covering $|\eta| < 2.0$ and $|\eta| < 1.4$, respectively. The TPC is a large cylindrical drift detector of radial and longitudinal size of about $85 < r < 250$ cm and $-250 < z < 250$ cm, respectively. It provides charged-hadron identification information via ionisation energy loss in the fill gas.

The data were collected in 2010 using a minimum-bias trigger requiring a hit in either the V0 scintillators or in the SPD detector, in coincidence with the arrival of proton bunches from both directions. The contamination from beam-induced background is removed offline by using the timing information and correlations in the V0 and SPD detectors, as discussed in details in [32].

The measurements reported here have been obtained for events having at least one charged particle produced with $p_{\rm T} > 0$ in the pseudorapidity interval $|\eta| < 1$ (INEL>0), corresponding to about 75% of the total inelastic cross-section. In order to study the multiplicity dependence of strange and multi-strange hadron production, the sample is divided into event classes based on the total charge deposited in the V0 detectors (V0M amplitude). The corresponding fractions of the INEL>0 cross-section are summarized in Table 1. Events used for the data analysis are further required to have a reconstructed vertex within $|z| < 10$ cm. Events containing more than one distinct vertex are tagged as pileup and are discarded. The remaining pileup fraction is estimated to be negligible, ranging from about 10^{-4} to 10^{-2} for the lowest and highest multiplicity classes, respectively. A total of about 100 million events has been utilised for the analysis. The mean pseudorapidity densities of primary charged particles $\langle {\rm d}N_{\rm ch}/{\rm d}\eta \rangle$ are measured at midrapidity, $|\eta| < 0.5$, for each event class using the technique described in [33]. The $\langle {\rm d}N_{\rm ch}/{\rm d}\eta \rangle$ values, corrected for acceptance and efficiency, as well as for contamination from secondary particles and combinatorial background, are listed in Table 1. The relative RMS width of the corresponding multiplicity distributions ranges from 68% to 30% for the lowest and highest multiplicity classes, respectively.

Strange $\rm K^0_S$, Λ and $\overline{\Lambda}$ and multi-strange Ξ^-, $\overline{\Xi}^+$, Ω^- and $\overline{\Omega}^+$ candidates are reconstructed via topological selection criteria and invariant-mass analysis of their characteristic weak decays [34]:

$$\begin{array}{rcll} \rm K^0_S & \rightarrow & \pi^+ + \pi^- & \text{B.R.} = (69.20 \pm 0.05)\ \% \\ \Lambda\ (\overline{\Lambda}) & \rightarrow & \rm p\ (\overline{p}) + \pi^-\ (\pi^+) & \text{B.R.} = (63.9 \pm 0.5)\ \% \\ \Xi^-\ (\overline{\Xi}^+) & \rightarrow & \Lambda\ (\overline{\Lambda}) + \pi^-\ (\pi^+) & \text{B.R.} = (99.887 \pm 0.035)\ \% \\ \Omega^-\ (\overline{\Omega}^+) & \rightarrow & \Lambda\ (\overline{\Lambda}) + \rm K^-\ (K^+) & \text{B.R.} = (67.8 \pm 0.7)\ \% \end{array}$$

Details on the analysis technique are described in [25, 35, 36]. The results are corrected for detector acceptance and reconstruction efficiency calculated using events from the PYTHIA6 (tune Perugia 0) MC generator [37] with particle transport performed via a GEANT3 [38] simulation of the ALICE detector. The contamination to Λ ($\overline{\Lambda}$) yields from weak decays of charged and neutral Ξ baryons (feed-down) is subtracted using a data-driven approach [25]. The study of systematic uncertainties follows the analysis described in [25, 35, 36]. Contributions common to all event classes ($N_{\rm ch}$-independent) are estimated and removed to determine the remaining uncertainties which are uncorrelated across different multiplicity intervals. The main sources of systematic uncertainty and their corresponding values are summarized in Table 2.

Particle/antiparticle production yields are identical within uncertainties. The $p_{\rm T}$ distributions of $\rm K^0_S$, $\Lambda + \overline{\Lambda}$, $\Xi^- + \overline{\Xi}^+$ and $\Omega^- + \overline{\Omega}^+$ (in the following denoted as $\rm K^0_S$, Λ, Ξ and Ω) measured in $|y| < 0.5$ are shown in Figure 1 for a selection of event classes with progressively increasing $\langle {\rm d}N_{\rm ch}/{\rm d}\eta \rangle$. The $p_{\rm T}$ spectra become harder as the multiplicity increases, with the hardening being more pronounced for higher mass particles. A similar observation was reported for p–Pb collisions [25] where several other analogies with Pb–Pb results are also consistent with the occurrence of collective behavior also in high-multiplicity p–Pb events [19–24, 27]. In HI collisions these observations are successfully described by

Table 1: Event multiplicity classes, their corresponding fraction of the INEL>0 cross-section ($\sigma/\sigma_{\mathrm{INEL}>0}$) and their corresponding $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ at midrapidity ($|\eta| < 0.5$). The value of $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ in the inclusive (INEL>0) class is 5.96 ± 0.23. The uncertainties are the quadratic sum of statistical and systematic contributions.

Class name	I	II	III	IV	V	VI	VII	VIII	IX	X
$\sigma/\sigma_{\mathrm{INEL}>0}$	0–0.95%	0.95–4.7%	4.7–9.5%	9.5–14%	14–19%	19–28%	28–38%	38–48%	48–68%	68–100%
$\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$	21.3±0.6	16.5±0.5	13.5±0.4	11.5±0.3	10.1±0.3	8.45±0.25	6.72±0.21	5.40±0.17	3.90±0.14	2.26±0.12

Table 2: Main sources and values of the relative systematic uncertainties (expressed in %) of the p_{T}-differential yields. The values are reported for low, intermediate and high p_{T}. The sums of the contributions common to all event classes are listed separately as N_{ch}-independent systematics.

Hadron		K^0_S			Λ ($\overline{\Lambda}$)			Ξ^- ($\overline{\Xi}^+$)			Ω^- ($\overline{\Omega}^+$)	
p_{T} (GeV/c)	0.05	6.2	11.0	0.5	3.7	7.2	0.8	2.1	5.8	1.2	2.8	4.7
Material budget	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Transport code		negligible		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Track selection	1.0	5.0	0.8	0.2	5.9	4.3	0.4	0.3	2.2	0.8	0.6	4.1
Topological selection	2.6	1.1	2.3	0.8	0.6	3.2	3.1	2.0	4.0	5.0	5.6	8.1
Particle identification	0.1	0.1	0.1	0.2	0.2	3.0	1.0	0.2	1.2	1.1	1.7	3.2
Efficiency determination	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Signal extraction	1.5	1.2	3.6	0.6	0.7	3.0	1.5	0.2	1.0	3.2	2.5	2.3
Proper lifetime	1.3	0.1	0.2	0.3	2.3	0.1	0.9	0.1	0.1	2.2	0.7	0.7
Competing decay rejection	negl.	0.7	1.3	negl.	1.0	6.2		not applicable		0.2	4.2	5.2
Feed-down correction		not applicable		3.3	2.1	4.3		negligible			negligible	
Total	5.6	6.9	6.4	5.8	8.2	11.2	5.9	5.0	6.7	7.9	9.0	12.1
Common (N_{ch}-independent)	5.0	5.9	4.4	5.4	7.8	9.9	5.2	4.5	6.2	7.3	8.7	11.6

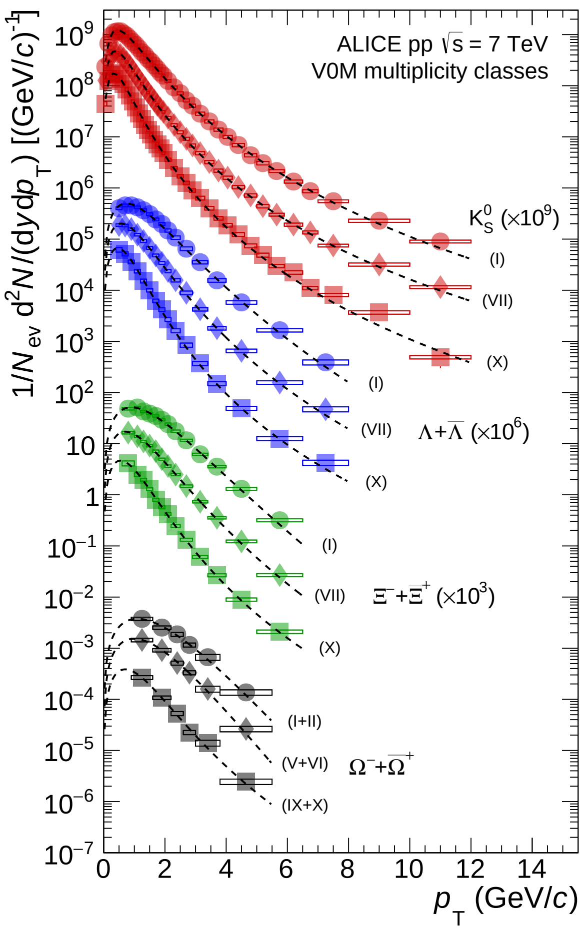

Fig. 1: (color online) p_{T}-differential yields of K^0_S, $\Lambda+\overline{\Lambda}$, $\Xi^-+\overline{\Xi}^+$ and $\Omega^-+\overline{\Omega}^+$ measured in $|y|<0.5$ for a selection of event classes, indicated by roman numbers in brackets (see Table 1). The data are scaled by different factors to improve the visibility. The dashed curves represent Tsallis-Lévy fits to each individual distribution to extract integrated yields.

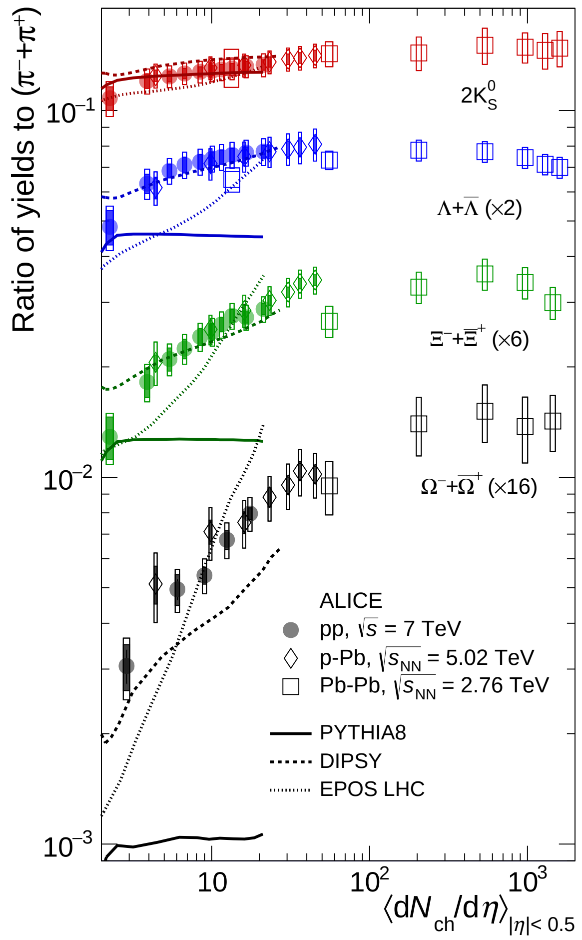

Fig. 2: (color online) p_{T}-integrated yield ratios of strange and multi-strange hadrons to $(\pi^++\pi^-)$ as a function of $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ measured in the rapidity interval $|y|<0.5$. The empty and dark-shaded boxes show the total systematic uncertainty and the contribution uncorrelated across multiplicity bins, respectively. The values are compared to calculations from MC models [39–43] and to results obtained in Pb–Pb and p–Pb collisions at the LHC [13, 25, 27]. For Pb–Pb results the ratio $2\Lambda\,/\,(\pi^++\pi^-)$ is shown.

models based on relativistic hydrodynamics. In this framework, the p_{T} distributions are effectively as due to particle emission from collectively expanding thermal sources [44, 45].

The blast-wave model [44] is employed to analyse the spectral shapes of K^0_S, Λ and Ξ in the common highest multiplicity class (class I). A simultaneous fit to all particles is performed following the approach discussed in [25] in the p_{T} ranges 0–1.5, 0.6–2.9 and 0.6–2.9 GeV/c, for K^0_S, Λ and Ξ, respectively. The best-fit describes the data to better than 5% in the respective fit ranges, consistent with particle production from a thermal source at temperature T_{fo} expanding with a common transverse velocity $\langle \beta_{\mathrm{T}} \rangle$. The resulting parameters, $T_{\mathrm{fo}} = 163 \pm 10$ MeV and $\langle \beta_{\mathrm{T}} \rangle = 0.49 \pm 0.02$, are remarkably similar to the ones obtained in p–Pb collisions for 20–40% [25], where $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ is also comparable.

The p_{T}-integrated yields are computed using the data in the measured ranges and extrapolations in the unmeasured regions. In order to extrapolate to the unmeasured region, the data were fitted with a Tsallis-

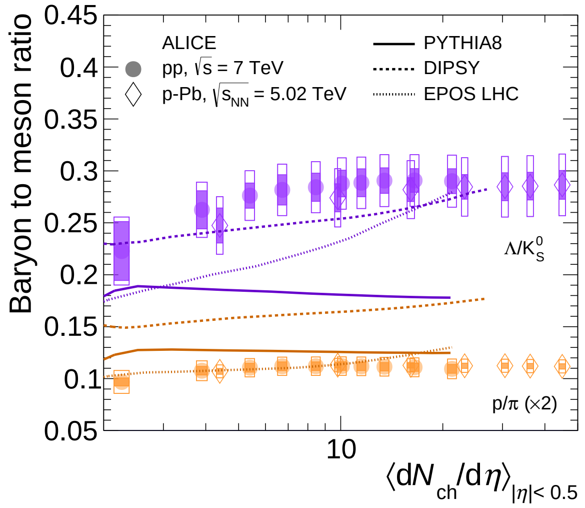

Fig. 3: (color online) Particle yield ratios $\Lambda/\mathrm{K}^0_S = (\Lambda+\overline{\Lambda})/2\mathrm{K}^0_S$ and $\mathrm{p}/\pi = (\mathrm{p}+\overline{\mathrm{p}})/(\pi^+ + \pi^-)$ as a function of $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ measured in the rapidity interval $|y| < 0.5$. The empty and dark-shaded boxes show the total systematic uncertainty and the contribution uncorrelated across multiplicity bins, respectively. The values are compared to calculations from MC models [39–43] in pp collisions at $\sqrt{s}$ = 7 TeV and to results obtained in p–Pb collisions at the LHC [25].

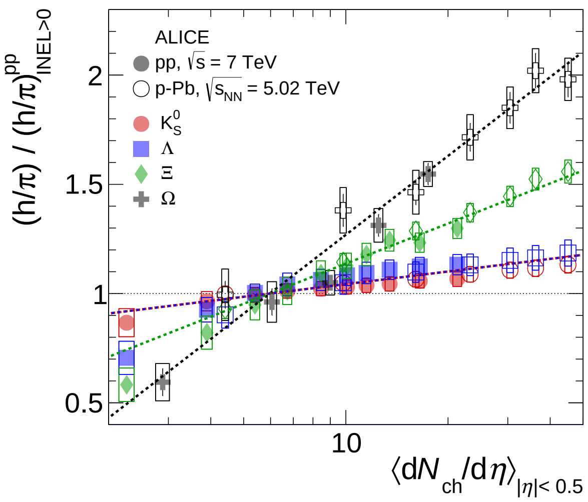

Fig. 4: (color online) Particle yield ratios to pions of strange and multi-strange hadrons normalised to the values measured in the inclusive INEL>0 pp sample, both in pp and in p–Pb collisions. The common systematic uncertainties cancel in the double-ratio. The empty boxes represent the remaining uncorrelated uncertainties. The lines represent a simultaneous fit of the results with the empirical scaling formula in Equation 1.

Lévy [25] parametrization, which gives the best description of the data for all particles and all event classes over the full p_{T} range (Figure 1). Several other fit functions [46] (Boltzmann, m_{T}-exponential, p_{T}-exponential, blast-wave, Fermi-Dirac, Bose-Einstein) are employed to estimate the corresponding systematic uncertainties. The fraction of extrapolated yield for highest(lowest) multiplicity event class is about 10(25)%, 16(36)%, 27(47)% for Λ, Ξ and Ω, respectively, and is negligible for K^0_S. The uncertainty on the extrapolation amounts to about 2(6)%, 3(10)%, 4(13)% of the total yield for Λ, Ξ and Ω, respectively, and it is negligible for K^0_S. The total systematic uncertainty on the p_{T}-integrated yields amounts to 5(9)%, 7(12)%, 6(14)% and 9(18)% for K^0_S, Λ, Ξ and Ω, respectively. A significant fraction of this uncertainty is common to all multiplicity classes and it is estimated to be about 5%, 6%, 6% and 9% for K^0_S, Λ, Ξ and Ω, respectively. In Figure 2, the ratios of the yields of K^0_S, Λ, Ξ and Ω to the pion $(\pi^+ + \pi^-)$ yield as a function of $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ are compared to p–Pb and Pb–Pb results at the LHC [13, 25, 27]. The results on pion production have been obtained for the same event classes reported here, following the analysis method discussed in [47]. A significant enhancement of strange to non-strange hadron production is observed with increasing particle multiplicity in pp collisions. The behaviour observed in pp collisions resembles that of p–Pb collisions at a slightly lower centre-of-mass energy [27], both in the values of the ratios and in their evolution with the event activity. This suggests that the origin of strangeness production in hadronic collisions is driven by the characteristics of the event activity rather than by the initial-state collision system or energy.

Figure 3 shows that the yield ratios $\Lambda/\mathrm{K}^0_S = (\Lambda+\overline{\Lambda})/2\mathrm{K}^0_S$ and $\mathrm{p}/\pi = (\mathrm{p}+\overline{\mathrm{p}})/(\pi^+ + \pi^-)$ do not change significantly with multiplicity, demonstrating that the observed enhanced production rates of strange hadrons with respect to pions is not due to the difference in the hadron masses. The results in Figures 2 and 3 are compared to calculations from MC models commonly used for pp collisions at the LHC: PYTHIA8 [39], EPOS LHC [40] and DIPSY [41–43]. We also compared with PHOJET [48] and HERWIG [49, 50] calculations whose results significantly deviate from the data and were therefore not included in the figures for clarity. The kinematic domain and the multiplicity selections are the same for MC and data, namely, dividing the INEL>0 sample into event classes based on the total charged-particle multiplicity in the V0 acceptance. The observation of a multiplicity-dependent enhancement of the production of strange hadrons along with the constant production of protons relative to pions cannot be simultaneously reproduced by any of the MC models commonly used at the LHC. The closest one, DIPSY, is a model where interaction between strings is allowed to form "color ropes" which are in turn expected to produce more strange particles and baryons.

To illustrate the dynamical evolution of the observed multiplicity-dependent production of strange hadrons, Figure 4 presents the yield ratios to pions divided by the values measured in the inclusive INEL>0 pp sample, both for pp and p–Pb results. The observed multiplicity-dependent enhancement with respect to the INEL>0 sample follows a hierarchy connected to the hadron strangeness. We evaluated the strangeness hierarchy quantitatively by fitting the data presented in Figure 4 with the empirical functional form

$$\frac{(h/\pi)}{(h/\pi)^{\mathrm{pp}}_{\mathrm{INEL}>0}} = 1 \, + \, a\,\mathrm{S}^{b}\,\log\left[\frac{\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle}{\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle^{\mathrm{pp}}_{\mathrm{INEL}>0}}\right], \tag{1}$$

where S is the number of (anti)strange quarks in the hadron, $(\mathrm{h}/\pi)^{\mathrm{pp}}_{\mathrm{INEL}>0}$ and $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle^{\mathrm{pp}}_{\mathrm{INEL}>0}$ are the measured hadron-to-pion ratio and the charged-particle multiplicity density in INEL>0 pp collisions, respectively, and a and b are free parameters. The fit describes the data well, yielding $a = 0.083 \pm 0.006$, $b = 1.67 \pm 0.09$, with a χ^2/ndf of 0.66.

In summary, we have presented the multiplicity dependence of the production of primary strange (K^0_S, Λ, $\overline{\Lambda}$) and multi-strange (Ξ^-, $\overline{\Xi}^+$, Ω^-, $\overline{\Omega}^+$) hadrons in pp collisions at $\sqrt{s}$ = 7 TeV. The results are obtained as a function of $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle$ measured at midrapidity for event classes selected on the basis of the total charge deposited in the forward region. The p_{T} spectra become harder as the multiplicity increases. The spectral shapes as well as the multiplicity and mass dependence are reminiscent of the patterns seen in p–Pb and Pb–Pb collisions at the LHC, which can be understood assuming a collective expansion of the system in the final state. The present data show for the first time in pp collisions that the p_{T}-integrated yields of strange and multi-strange particles relative to pions increase significantly with multiplicity. These particle ratios are similar to those found in p–Pb collisions at the same multiplicity densities [27]. The observed enhancement increases with strangeness content rather than with mass or baryon number of the hadron. The data cannot be reproduced by any of the MC models commonly used, suggesting that further developments are needed for a complete microscopic understanding of strangeness production and indicating the presence of a phenomenon novel in high-multiplicity pp collisions. The evolution of strangeness enhancement seen at the LHC, smoothly increasing over three orders of magnitude in $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle$ from low multiplicity pp over p–Pb to central Pb–Pb collisions, may point towards a common underlying physics mechanism which gradually compensates the strangeness suppression in fragmentation. Further studies extending to higher multiplicity in small systems are essential, as they would allow one to assess if strangeness production saturates at the thermal equilibrium values predicted by the grand canonical statistical model [14, 15] or if it continues increasing. In any case, the remarkable similarity of strange particle production in pp, p–Pb and Pb–Pb collisions complements previous measurements in pp, which also exhibit characteristic features known from high-energy HI collisions [19–25, 27–29] and understood as connected to the formation of a deconfined QCD phase at high temperature and energy density. Whether the combination of these observations can be interpreted as signal of the progressive onset of a QGP medium in small systems is still an open question. It is therefore crucial to understand which microscopic mechanisms could lead to the observed phenomena in pp collisions and to what extent such mechanisms would contribute to the observed effects in HI collisions.

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References

[1] J. Rafelski and B. Müller, "Strangeness Production in the Quark–Gluon Plasma," *Phys. Rev. Lett.* **48** (1982) 1066. [Erratum: Phys. Rev. Lett. 56, 2334 (1986)].

[2] P. Koch, J. Rafelski, and W. Greiner, "Strange hadron in hot nuclear matter," *Phys. Lett.* **B123** (1983) 151–154.

[3] P. Koch, B. Muller, and J. Rafelski, "Strangeness in Relativistic Heavy Ion Collisions," *Phys. Rept.* **142** (1986) 167–262.

[4] E. Andersen *et al.*, “Enhancement of central Λ, Ξ and Ω yields in Pb–Pb collisions at 158 AGeV/c,” *Phys. Lett.* **B433** (1998) 209–216.

[5] **WA97** Collaboration, E. Andersen *et al.*, “Strangeness enhancement at mid-rapidity in Pb–Pb collisions at 158 AGeV/c,” *Phys. Lett.* **B449** (1999) 401–406.

[6] **NA57** Collaboration, F. Antinori *et al.*, “Energy dependence of hyperon production in nucleus nucleus collisions at SPS,” *Phys. Lett.* **B595** (2004) 68–74, `arXiv:nucl-ex/0403022 [nucl-ex]`.

[7] **NA49** Collaboration, S. V. Afanasiev *et al.*, “Ξ and $\bar{\Xi}$ production in central Pb+Pb collisions at 158 GeV/c per nucleon,” *Phys. Lett.* **B538** (2002) 275–281, `arXiv:hep-ex/0202037 [hep-ex]`.

[8] **NA49** Collaboration, T. Anticic *et al.*, “Λ and $\bar{\Lambda}$ production in central Pb–Pb collisions at 40 AGeV, 80 AGeV and 158 AGeV,” *Phys. Rev. Lett.* **93** (2004) 022302, `arXiv:nucl-ex/0311024 [nucl-ex]`.

[9] **STAR** Collaboration, J. Adams *et al.*, “Multistrange baryon production in Au–Au collisions at $\sqrt{s_{\rm NN}}$ = 130 GeV,” *Phys. Rev. Lett.* **92** (2004) 182301, `arXiv:nucl-ex/0307024 [nucl-ex]`.

[10] **STAR** Collaboration, J. Adams *et al.*, “Scaling Properties of Hyperon Production in Au+Au Collisions at $\sqrt{s}$ = 200 GeV,” *Phys. Rev. Lett.* **98** (2007) 062301, `arXiv:nucl-ex/0606014 [nucl-ex]`.

[11] **STAR** Collaboration, B. I. Abelev *et al.*, “Enhanced strange baryon production in Au+Au collisions compared to p+p at $\sqrt{s}$ = 200-GeV,” *Phys. Rev.* **C77** (2008) 044908, `arXiv:0705.2511 [nucl-ex]`.

[12] **NA57** Collaboration, F. Antinori *et al.*, “Strangeness enhancements at central rapidity in 40 A GeV/c Pb-Pb collisions,” *J. Phys.* **G37** (2010) 045105, `arXiv:1001.1884 [nucl-ex]`.

[13] **ALICE** Collaboration, B. Abelev *et al.*, “Multi-strange baryon production at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV,” *Phys. Lett.* **B728** (2014) 216–227, `arXiv:1307.5543 [nucl-ex]`. [Erratum: Phys. Lett. B734, 409 (2014)].

[14] J. Cleymans, I. Kraus, H. Oeschler, K. Redlich, and S. Wheaton, “Statistical model predictions for particle ratios at $\sqrt{s_{\rm NN}}$ = 5.5-TeV,” *Phys. Rev.* **C74** (2006) 034903, `arXiv:hep-ph/0604237 [hep-ph]`.

[15] A. Andronic, P. Braun-Munzinger, and J. Stachel, “Thermal hadron production in relativistic nuclear collisions: The Hadron mass spectrum, the horn, and the QCD phase transition,” *Phys. Lett.* **B673** (2009) 142–145, `arXiv:0812.1186 [nucl-th]`. [Erratum: Phys. Lett.B678,516(2009)].

[16] K. Redlich and A. Tounsi, “Strangeness enhancement and energy dependence in heavy ion collisions,” *Eur. Phys. J.* **C24** (2002) 589–594, `arXiv:hep-ph/0111261 [hep-ph]`.

[17] F. Becattini and J. Manninen, “Strangeness production from SPS to LHC,” *J. Phys.* **G35** (2008) 104013, `arXiv:0805.0098 [nucl-th]`.

[18] J. Aichelin and K. Werner, “Centrality Dependence of Strangeness Enhancement in Ultrarelativistic Heavy Ion Collisions: A Core-Corona Effect,” *Phys. Rev.* **C79** (2009) 064907, `arXiv:0810.4465 [nucl-th]`. [Erratum: Phys. Rev.C81,029902(2010)].

[19] **CMS** Collaboration, V. Khachatryan *et al.*, "Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC," *JHEP* **09** (2010) 091, arXiv:1009.4122 [hep-ex].

[20] **CMS** Collaboration, S. Chatrchyan *et al.*, "Observation of long-range near-side angular correlations in proton-lead collisions at the LHC," *Phys. Lett.* **B718** (2013) 795–814, arXiv:1210.5482 [nucl-ex].

[21] **ALICE** Collaboration, B. Abelev *et al.*, "Long-range angular correlations on the near and away side in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV," *Phys. Lett.* **B719** (2013) 29–41, arXiv:1212.2001 [nucl-ex].

[22] **ATLAS** Collaboration, G. Aad *et al.*, "Observation of Associated Near-Side and Away-Side Long-Range Correlations in $\sqrt{s_{\rm NN}}$=5.02TeV Proton-Lead Collisions with the ATLAS Detector," *Phys. Rev. Lett.* **110** no. 18, (2013) 182302, arXiv:1212.5198 [hep-ex].

[23] **ATLAS** Collaboration, G. Aad *et al.*, "Measurement with the ATLAS detector of multi-particle azimuthal correlations in p+Pb collisions at $\sqrt{s_{\rm NN}}$=5.02 TeV," *Phys. Lett.* **B725** (2013) 60–78, arXiv:1303.2084 [hep-ex].

[24] **CMS** Collaboration, S. Chatrchyan *et al.*, "Multiplicity and transverse momentum dependence of two- and four-particle correlations in pPb and PbPb collisions," *Phys. Lett.* **B724** (2013) 213–240, arXiv:1305.0609 [nucl-ex].

[25] **ALICE** Collaboration, B. Abelev *et al.*, "Multiplicity Dependence of Pion, Kaon, Proton and Lambda Production in p–Pb Collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV," *Phys. Lett.* **B728** (2014) 25–38, arXiv:1307.6796 [nucl-ex].

[26] **ALICE** Collaboration, B. B. Abelev *et al.*, "Long-range angular correlations of π, K and p in p-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV," *Phys. Lett.* **B726** (2013) 164–177, arXiv:1307.3237 [nucl-ex].

[27] **ALICE** Collaboration, J. Adam *et al.*, "Multi-strange baryon production in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV," arXiv:1512.07227 [nucl-ex].

[28] **CMS** Collaboration, V. Khachatryan *et al.*, "Multiplicity and rapidity dependence of strange hadron production in pp, pPb, and PbPb collisions at the LHC," arXiv:1605.06699 [nucl-ex].

[29] **CMS** Collaboration, V. Khachatryan *et al.*, "Evidence for collectivity in pp collisions at the LHC," arXiv:1606.06198 [nucl-ex].

[30] **ALICE** Collaboration, K. Aamodt *et al.*, "The ALICE experiment at the CERN LHC," *JINST* **3** (2008) S08002.

[31] **ALICE** Collaboration, B. Abelev *et al.*, "K^0_S and Λ production in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV," *Phys. Rev. Lett.* **111** (2013) 222301, arXiv:1307.5530 [nucl-ex].

[32] **ALICE** Collaboration, B. Abelev *et al.*, "Performance of the ALICE Experiment at the CERN LHC," *Int. J. Mod. Phys.* **A29** (2014) 1430044, arXiv:1402.4476 [nucl-ex].

[33] **ALICE** Collaboration, B. Abelev *et al.*, "Pseudorapidity density of charged particles in p+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV," *Phys. Rev. Lett.* **110** no. 3, (2013) 032301, arXiv:1210.3615 [nucl-ex].

[34] **Particle Data Group** Collaboration, K. A. Olive *et al.*, "Review of Particle Physics," *Chin. Phys.* **C38** (2014) 090001.

[35] **ALICE** Collaboration, K. Aamodt *et al.*, "Strange particle production in proton-proton collisions at $\sqrt{s} = 0.9$ TeV with ALICE at the LHC," *Eur. Phys. J.* **C71** (2011) 1594, arXiv:1012.3257 [hep-ex].

[36] **ALICE** Collaboration, B. Abelev *et al.*, "Multi-strange baryon production in pp collisions at $\sqrt{s} = 7$ TeV with ALICE," *Phys. Lett. B* **712** (2012) 309–318, arXiv:1204.0282 [nucl-ex].

[37] P. Z. Skands, "Tuning Monte Carlo Generators: The Perugia Tunes," *Phys. Rev.* **D82** (2010) 074018, arXiv:1005.3457 [hep-ph].

[38] R. Brun, F. Bruyant, F. Carminati, S. Giani, M. Maire, A. McPherson, G. Patrick, and L. Urban, "GEANT Detector Description and Simulation Tool," CERN-W5013, CERN-W-5013, W5013, W-5013.

[39] T. Sjöstrand, S. Mrenna, and P. Z. Skands, "A Brief Introduction to PYTHIA 8.1," *Comput. Phys. Commun.* **178** (2008) 852–867, arXiv:0710.3820 [hep-ph].

[40] T. Pierog, I. Karpenko, J. Katzy, E. Yatsenko, and K. Werner, "EPOS LHC : test of collective hadronization with LHC data," arXiv:1306.0121 [hep-ph].

[41] C. Flensburg, G. Gustafson, and L. Lonnblad, "Inclusive and Exclusive Observables from Dipoles in High Energy Collisions," *JHEP* **08** (2011) 103, arXiv:1103.4321 [hep-ph].

[42] C. Bierlich, G. Gustafson, L. Lnnblad, and A. Tarasov, "Effects of Overlapping Strings in pp Collisions," *JHEP* **03** (2015) 148, arXiv:1412.6259 [hep-ph].

[43] C. Bierlich and J. R. Christiansen, "Effects of Colour Reconnection on Hadron Flavour Observables," *Phys. Rev.* **D92** (2015) 094010, arXiv:1507.02091 [hep-ph].

[44] E. Schnedermann, J. Sollfrank, and U. W. Heinz, "Thermal phenomenology of hadrons from 200 A/GeV S+S collisions," *Phys. Rev.* **C48** (1993) 2462–2475, arXiv:nucl-th/9307020 [nucl-th].

[45] U. W. Heinz, "Concepts of heavy ion physics," in *2002 European School of high-energy physics, Pylos, Greece, 25 Aug-7 Sep 2002: Proceedings*, pp. 165–238. 2004. arXiv:hep-ph/0407360 [hep-ph]. http://doc.cern.ch/yellowrep/CERN-2004-001.

[46] **STAR** Collaboration, B. Abelev *et al.*, "Systematic Measurements of Identified Particle Spectra in pp, d+Au and Au+Au Collisions from STAR," *Phys. Rev.* **C79** (2009) 034909, arXiv:0808.2041 [nucl-ex].

[47] **ALICE** Collaboration, J. Adam *et al.*, "Measurement of pion, kaon and proton production in proton-proton collisions at $\sqrt{s} = 7$ TeV," *Eur. Phys. J. C* **75** no. 5, (2015) 226, arXiv:1504.00024 [nucl-ex].

[48] R. Engel, J. Ranft, and S. Roesler, "Hard diffraction in hadron hadron interactions and in photoproduction," *Phys. Rev.* **D52** (1995) 1459–1468, arXiv:hep-ph/9502319 [hep-ph].

[49] M. Bahr *et al.*, "Herwig++ Physics and Manual," *Eur. Phys. J.* **C58** (2008) 639–707, arXiv:0803.0883 [hep-ph].

[50] J. Bellm *et al.*, "Herwig 7.0/Herwig++ 3.0 release note," *Eur. Phys. J.* **C76** no. 4, (2016) 196, arXiv:1512.01178 [hep-ph].

A The ALICE Collaboration

J. Adam[40] , D. Adamová[86] , M.M. Aggarwal[90] , G. Aglieri Rinella[36] , M. Agnello[32 ,112] , N. Agrawal[49] , Z. Ahammed[135] , S. Ahmad[19] , S.U. Ahn[70] , S. Aiola[139] , A. Akindinov[60] , S.N. Alam[135] , D.S.D. Albuquerque[123] , D. Aleksandrov[82] , B. Alessandro[112] , D. Alexandre[103] , R. Alfaro Molina[66] , A. Alici[12 ,106] , A. Alkin[3] , J. Alme[18 ,38] , T. Alt[43] , S. Altinpinar[18] , I. Altsybeev[134] , C. Alves Garcia Prado[122] , M. An[7] , C. Andrei[80] , H.A. Andrews[103] , A. Andronic[99] , V. Anguelov[96] , T. Antičić[100] , F. Antinori[109] , P. Antonioli[106] , L. Aphecetche[115] , H. Appelshäuser[55] , S. Arcelli[27] , R. Arnaldi[112] , O.W. Arnold[37 ,95] , I.C. Arsene[22] , M. Arslandok[55] , B. Audurier[115] , A. Augustinus[36] , R. Averbeck[99] , M.D. Azmi[19] , A. Badalà[108] , Y.W. Baek[69] , S. Bagnasco[112] , R. Bailhache[55] , R. Bala[93] , S. Balasubramanian[139] , A. Baldisseri[15] , R.C. Baral[63] , A.M. Barbano[26] , R. Barbera[28] , F. Barile[33] , G.G. Barnaföldi[138] , L.S. Barnby[103 ,36] , V. Barret[72] , P. Bartalini[7] , K. Barth[36] , J. Bartke[119 ,i], E. Bartsch[55] , M. Basile[27] , N. Bastid[72] , S. Basu[135] , B. Bathen[56] , G. Batigne[115] , A. Batista Camejo[72] , B. Batyunya[68] , P.C. Batzing[22] , I.G. Bearden[83] , H. Beck[55 ,96] , C. Bedda[112] , N.K. Behera[52] , I. Belikov[57] , F. Bellini[27] , H. Bello Martinez[2] , R. Bellwied[124] , R. Belmont[137] , E. Belmont-Moreno[66] , L.G.E. Beltran[121] , V. Belyaev[77] , G. Bencedi[138] , S. Beole[26] , I. Berceanu[80] , A. Bercuci[80] , Y. Berdnikov[88] , D. Berenyi[138] , R.A. Bertens[59] , D. Berzano[36] , L. Betev[36] , A. Bhasin[93] , I.R. Bhat[93] , A.K. Bhati[90] , B. Bhattacharjee[45] , J. Bhom[119] , L. Bianchi[124] , N. Bianchi[74] , C. Bianchin[137] , J. Bielčík[40] , J. Bielčíková[86] , A. Bilandzic[83 ,37 ,95] , G. Biro[138] , R. Biswas[4] , S. Biswas[4 ,81] , S. Bjelogrlic[59] , J.T. Blair[120] , D. Blau[82] , C. Blume[55] , F. Bock[76 ,96] , A. Bogdanov[77] , H. Bøggild[83] , L. Boldizsár[138] , M. Bombara[41] , M. Bonora[36] , J. Book[55] , H. Borel[15] , A. Borissov[98] , M. Borri[126 ,85] , F. Bossú[67] , E. Botta[26] , C. Bourjau[83] , P. Braun-Munzinger[99] , M. Bregant[122] , T. Breitner[54] , T.A. Broker[55] , T.A. Browning[97] , M. Broz[40] , E.J. Brucken[47] , E. Bruna[112] , G.E. Bruno[33] , D. Budnikov[101] , H. Buesching[55] , S. Bufalino[32 ,36] , P. Buncic[36] , O. Busch[130] , Z. Buthelezi[67] , J.B. Butt[16] , J.T. Buxton[20] , J. Cabala[117] , D. Caffarri[36] , X. Cai[7] , H. Caines[139] , L. Calero Diaz[74] , A. Caliva[59] , E. Calvo Villar[104] , P. Camerini[25] , F. Carena[36] , W. Carena[36] , F. Carnesecchi[27] , J. Castillo Castellanos[15] , A.J. Castro[127] , E.A.R. Casula[24] , C. Ceballos Sanchez[9] , J. Cepila[40] , P. Cerello[112] , J. Cerkala[117] , B. Chang[125] , S. Chapeland[36] , M. Chartier[126] , J.L. Charvet[15] , S. Chattopadhyay[135] , S. Chattopadhyay[102] , A. Chauvin[95 ,37] , V. Chelnokov[3] , M. Cherney[89] , C. Cheshkov[132] , B. Cheynis[132] , V. Chibante Barroso[36] , D.D. Chinellato[123] , S. Cho[52] , P. Chochula[36] , K. Choi[98] , M. Chojnacki[83] , S. Choudhury[135] , P. Christakoglou[84] , C.H. Christensen[83] , P. Christiansen[34] , T. Chujo[130] , S.U. Chung[98] , C. Cicalo[107] , L. Cifarelli[12 ,27] , F. Cindolo[106] , J. Cleymans[92] , F. Colamaria[33] , D. Colella[61 ,36] , A. Collu[76] , M. Colocci[27] , G. Conesa Balbastre[73] , Z. Conesa del Valle[53] , M.E. Connors[ii,139] , J.G. Contreras[40] , T.M. Cormier[87] , Y. Corrales Morales[26 ,112] , I. Cortés Maldonado[2] , P. Cortese[31] , M.R. Cosentino[122] , F. Costa[36] , J. Crkovska[53] , P. Crochet[72] , R. Cruz Albino[11] , E. Cuautle[65] , L. Cunqueiro[56 ,36] , T. Dahms[95 ,37] , A. Dainese[109] , M.C. Danisch[96] , A. Danu[64] , D. Das[102] , I. Das[102] , S. Das[4] , A. Dash[81] , S. Dash[49] , S. De[122] , A. De Caro[12 ,30] , G. de Cataldo[105] , C. de Conti[122] , J. de Cuveland[43] , A. De Falco[24] , D. De Gruttola[12 ,30] , N. De Marco[112] , S. De Pasquale[30] , R.D. De Souza[123] , A. Deisting[96 ,99] , A. Deloff[79] , E. Dénes[138 ,i], C. Deplano[84] , P. Dhankher[49] , D. Di Bari[33] , A. Di Mauro[36] , P. Di Nezza[74] , B. Di Ruzza[109] , M.A. Diaz Corchero[10] , T. Dietel[92] , P. Dillenseger[55] , R. Divià[36] , Ø. Djuvsland[18] , A. Dobrin[84 ,64] , D. Domenicis Gimenez[122] , B. Dönigus[55] , O. Dordic[22] , T. Drozhzhova[55] , A.K. Dubey[135] , A. Dubla[59] , L. Ducroux[132] , P. Dupieux[72] , R.J. Ehlers[139] , D. Elia[105] , E. Endress[104] , H. Engel[54] , E. Epple[139] , B. Erazmus[115] , I. Erdemir[55] , F. Erhardt[131] , B. Espagnon[53] , M. Estienne[115] , S. Esumi[130] , J. Eum[98] , D. Evans[103] , S. Evdokimov[113] , G. Eyyubova[40] , L. Fabbietti[95 ,37] , D. Fabris[109] , J. Faivre[73] , A. Fantoni[74] , M. Fasel[76] , L. Feldkamp[56] , A. Feliciello[112] , G. Feofilov[134] , J. Ferencei[86] , A. Fernández Téllez[2] , E.G. Ferreiro[17] , A. Ferretti[26] , A. Festanti[29] , V.J.G. Feuillard[15 ,72] , J. Figiel[119] , M.A.S. Figueredo[126 ,122] , S. Filchagin[101] , D. Finogeev[58] , F.M. Fionda[24] , E.M. Fiore[33] , M. Floris[36] , S. Foertsch[67] , P. Foka[99] , S. Fokin[82] , E. Fragiacomo[111] , A. Francescon[36] , A. Francisco[115] , U. Frankenfeld[99] , G.G. Fronze[26] , U. Fuchs[36] , C. Furget[73] , A. Furs[58] , M. Fusco Girard[30] , J.J. Gaardhøje[83] , M. Gagliardi[26] , A.M. Gago[104] , K. Gajdosova[83] , M. Gallio[26] , C.D. Galvan[121] , D.R. Gangadharan[76] , P. Ganoti[91] , C. Gao[7] , C. Garabatos[99] , E. Garcia-Solis[13] , K. Garg[28] , C. Gargiulo[36] , P. Gasik[95 ,37] , E.F. Gauger[120] , M. Germain[115] , M. Gheata[36 ,64] , P. Ghosh[135] , S.K. Ghosh[4] , P. Gianotti[74] , P. Giubellino[112 ,36] , P. Giubilato[29] , E. Gladysz-Dziadus[119] , P. Glässel[96] , D.M. Goméz Coral[66] , A. Gomez Ramirez[54] , A.S. Gonzalez[36] , V. Gonzalez[10] , P. González-Zamora[10] , S. Gorbunov[43] , L. Görlich[119] , S. Gotovac[118] , V. Grabski[66] , O.A. Grachov[139] , L.K. Graczykowski[136] , K.L. Graham[103] , A. Grelli[59] , A. Grigoras[36] , C. Grigoras[36] , V. Grigoriev[77] , A. Grigoryan[1] , S. Grigoryan[68] , B. Grinyov[3] , N. Grion[111] , J.M. Gronefeld[99] , J.F. Grosse-Oetringhaus[36] , R. Grosso[99] , L. Gruber[114] , F. Guber[58] , R. Guernane[73] , B. Guerzoni[27] , K. Gulbrandsen[83] , T. Gunji[129] , A. Gupta[93] , R. Gupta[93] , R. Haake[56 ,36] , C. Hadjidakis[53] , M. Haiduc[64] , H. Hamagaki[129] , G. Hamar[138] , J.C. Hamon[57] , J.W. Harris[139] , A. Harton[13] , D. Hatzifotiadou[106] , S. Hayashi[129] , S.T. Heckel[55] , E. Hellbär[55] , H. Helstrup[38] , A. Herghelegiu[80] , G. Herrera Corral[11] ,

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